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Rolling of AZ31 magnesium alloy strip using induction heating rolls

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Abstract

Magnesium alloy strips are difficult to produce through cold forming process due to their poor deformation ability. In this article, fabrication of AZ31 alloy strip by Hot-roller warm rolling process was studied. Experiment using induction heating rolls was carried out, its results confirmed that this technique can improve plasticity of AZ31, and reduce its processing difficulty. The temperature change in deformation zone during Hot-roller warm rolling with a roll temperature of 150~350 °C was analyzed by numerical simulation. Finally, a prediction equation of deformation temperature in strips during Hot-roller warm rolling process was established.

Keywords: Finite element simulation; AZ31 alloy; Hot-roller warm rolling process; Temperature field

1. Introduction

Magnesium alloy strips are being increasingly used in electronics, automobile and aerospace industries, due to their low density, high specific strength, good damping capacity and outstanding thermal diffusivity, etc. However, being one of hexagonal close-packed (HCP) crystal structure metals, magnesium alloys exhibits poor plasticity at room temperature. Generally, magnesium alloy strips are rolled at elevated temperatures. Rolling process such as hot rolling and conventional warm rolling are used in rolling magnesium alloy strip have been frequently reported [1]. But there will be a lot of problems, for example, heat working temperatures range of magnesium alloys is

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narrow [2], moreover, their heating and cooling velocities are much quicker than those of other metals, due to its lowest volume heat capacity and high heat conductivity coefficient. All above brings many difficulties to the forming of magnesium alloy strips.

In recent year, a new rolling technology called Hot-roller warm rolling was proposed [3]. By this idea, the strip is heated by contacting heat transfer with hot rolls at deformation zone, to achieve a warm-rolling temperature and improve process ability. Yu et al. [4] studied the effect of this warm rolling method used in magnesium alloy strip forming by using FEM, but without any practical experiment. In this article, the experiment and simulation of AZ31 alloy strip warm rolling by Hot-roller was carried out, and an accurate model was established to predict the temperature of the deformation zone under different rolling conditions.

2. Application of Hot-roller warm rolling on AZ31 strip forming

2.1. Experimental equipment

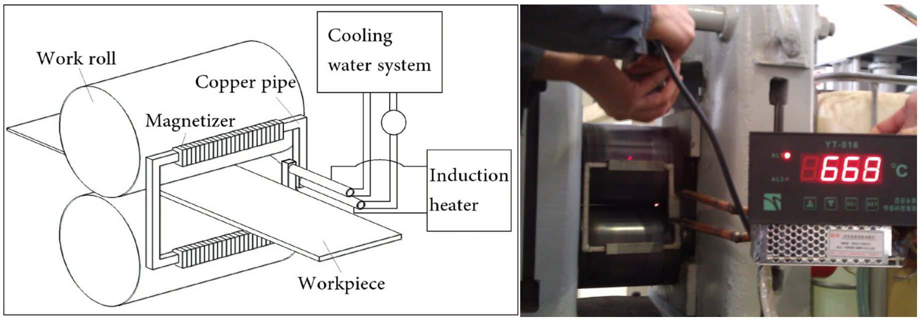

Fig. 1. (a) Sketch of Hot-roller process system; (b)Induction heating on 2-high mill work rolls.

It has been reported that induction heating technique had been used for heating rolls [3], the equipment has undergone several improvements. As Fig. 1.(a) shows, the latest induction heating equipment consists of: (i) A square shape copper pipe; (ii) Magnetizers; (iii) High-frequency induction heater; (iv)Cooling water system.

The square shape copper pipe was used as induction coil. Induction heater exerts high frequency alternating current on the pipe, in where alternating magnetic field generate. An entire row of magnetizers were attached to the pipe to gather the magnetic field for heating the rolls surface efficiently.

The entire apparatus can be assembled on all kinds of rolling mill to heat work rolls. Fig. 1(b) shows the equipment applied in 2-high roll mill, it was easily and quickly to raise the temperature of roll surface to 668 °C by 40kW induction heater.

2.2. Experimental results

An online induction heating device was installed on a Φ90 / 200 × 200 mm four high mill，the rolling velocity of this mill is 0.05 m/s. Hot-rolled AZ31 alloy strip with a thickness of 3 and 1.5 mm were used in the study. The experimental procedures were conducted in the following sequence:

1. By feedback controlling the power of induction heater, the rolls surface was kept at constant temperature, which were 150, 200 and 250 °C in the experiment.
2. Then the room temperature strips were warm-rolled under different reduction ratios at constant roll temperature.
3. As soon as the rolling finished, the temperature of strips were measured.

Five reduction ratios levels (5%, 10%, 15%, 20%, 25%) and three roll temperature levels (150 °C, 200 °C, 250 °C) were analyzed. Fig. 2 summarizes the experimental results in terms of finish rolling temperature. The upper limits were obtained using the highest reduction ratios (25%), whereas the lower limits used the lowest reduction ratios (5%). The following points can be noted:

(i) When the initial thickness and reduction ratio are constant, with the increasing of roll temperature, the temperature in strips increased linearly. The mean temperature of 1.5mm strips under 10% reduction ratio increased from 116 °C to 193 °C when the rolls temperature increased from 150 °C to 250 °C. (ii) When the reduction ratio and roll temperature are constant, the finish rolling temperatures of 1.5mm strips were 15~30 °C higher than the ones of 3.0mm strips. (iii) When the initial thickness and roll temperature are constant, with the increasing of the reduction ratio, the finish rolling temperature of strips increased. When adopting elevated roll temperature, the effect of reduction ratio on strip temperature was markedly improved, this is because a heavy reduction will cause contact arc length longer, so the more heat conducted from hot rolls to strip.

The experiment also found that when the roll temperature was 250 °C, none of the strips appeared crack. After multi-pass continuous Hot-roller warm rolling without any heat treatment, The AZ31 strip thickness was reduced from 1.530 mm to 0.147 mm and from 2.971 mm to 0.667 mm, even thinner. So it is sufficient that setting the roll temperature range as 150~350 °C to study, In addition, if the temperature is too high, excessive grain growth may cause a poor mechanical property. So, the range 500~580 °C studied by Yu is not very reasonable.

Then, the temperature change in deformation zone during Hot-roller warm rolling with roll temperature of 150~350 °C was analyzed by numerical simulation, a 3D coupled thermo-mechanical models was performed using ABAQUS/explicit.

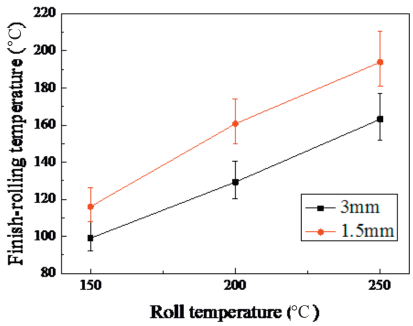

Fig. 2. Effect of roll temperature, reduction ratio and initial thickness on finish-rolling temperature.

3. Analysis of deformation zone temperature field

3.1. Model and parameters

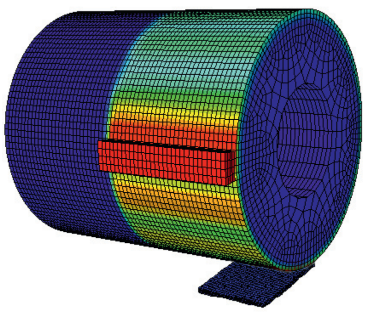

Fig. 3. Geometry model and FE meshing of process.

A FE model was established in terms of the same parameter of the above experiment. In the models, since the symmetry of strip rolling processes, a half of rolling model was employed, and a modeling method of equivalent hollow roller [5] was adopted to decrease computing workload. The plastic property of AZ31 was determined based on a tensile test carried out by Chang et al. [6], and temperature field of roll was assigned according to previous research on induction heating process [7]. The main material parameters are listed in Table 1.

Table 1. Material parameters.

Parameters	AZ31 alloy strip	Roll(GCr15)
Density, kg/m^3	1755	7930
Elastic modulus, GPa	41	215
Poisson□s ratio	0.3	0.3
specific heat, J/(kg°C)	1150	460
Heat transfer coefficient, W/(m°C)	110.5	17.6

In the simulations, the influence of roll temperature (150~350 °C), rolling velocity (0.01-1 m/s), reduction ratio (5-80%), and initial strip thickness (0.6-10 mm) on the mean temperature of strip in the rolling deformation zone were analyzed. As you can see, some parameters can't achieve in laboratory were also studied, in order to obtain a prediction equation of deformation temperature by which the Hot-roller warm rolling process can be guided.

Table 2. Comparison between calculated value and measured value.

Sample parameters	Calculated value	Measured value
150 °C -0.05 m/s-10%-1.5 mm	118.99	111
200 °C -0.05 m/s-15%-1.5 mm	157.71	148
250 °C -0.05 m/s-20%-3.0 mm	166.87	159

Table2 shows the comparison between calculated value and measured value, it seems that the measured values are always lower than the calculated ones, that is because the time interval between finish rolling and temperature data acquisition exists, and the strips temperature could not avoid dropping. When the heat convection and radiation were taken into account by calculating, the FE model turns out to be accurately.

3.2. Results and discussion

In this article, the temperature of deformation(T_D) was considered as the mean temperature of six points in the centre of the rolling zone.

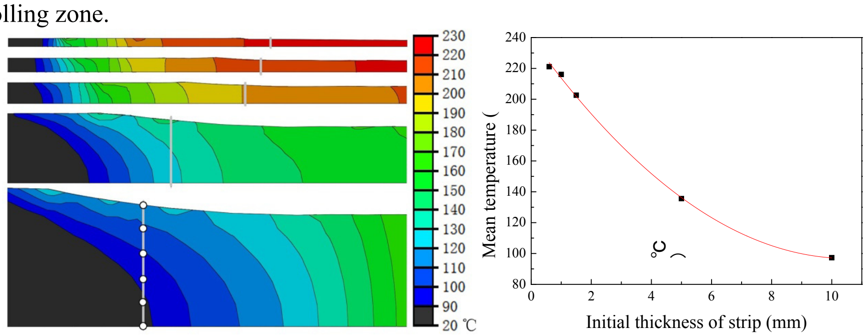

Fig. 4. (a) Temperature field in deformation zone under various initial strip thickness of 0.6 mm, 1 mm, 1.5 mm, 5 mm, 10 mm; (b) Relationship between initial strip thickness and the mean temperature of deformation zone.

Fig. 4(a) shows the thermal field of AZ31 alloy strips in the rolling deformation zone under a variety of initial strip thicknesses(h_0), where the temperature roll(T_R) is 250 °C, reduction ratio(ε) 20%, and rolling velocity(v) 0.05 m/s. With reduction of the initial strip thickness, the thermal field of strips in the rolling deformation zone becomes more uniform. Fig. 4(b) shows the relationship between T_D and h_0, it could be described by Eq. (1).

$$T_D = 239.553 - 27.084h_0 + 1.285h_0^2\,. \tag{1}$$

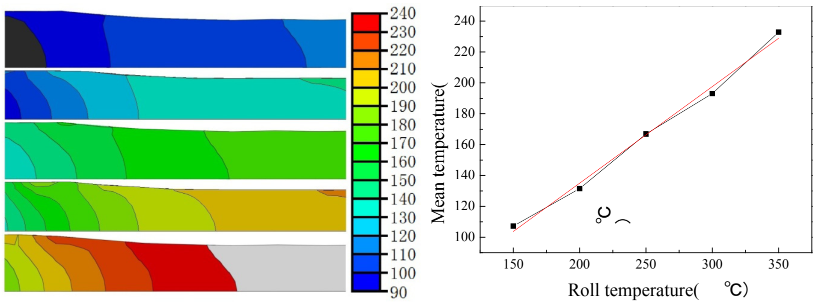

Fig. 5. (a)Temperature field in deformation zone under the roll temperature of 150 °C, 200 °C, 250 °C, 300 °C, 350 °C; (b) Relationship between roll temperature and the mean temperature of deformation zone.

Fig. 5(a) shows the thermal field of strips in the rolling deformation zones under various roll temperatures, where v = 0.05 m/s, h_0 = 3 mm, and ε = 20%. With increasing the roll temperatures, the temperature in rolled strips markedly increases. Fig. 4(b) shows the relationship between T_D and T_R, it could be described by Eq. (2).

$$T_D = 9.943 + 0.626T_R\,. \tag{2}$$

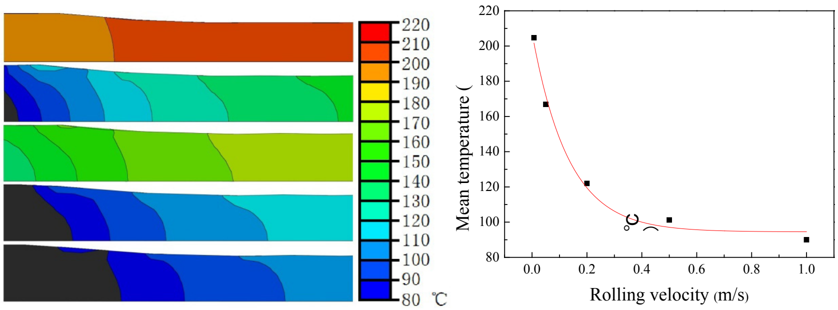

Fig. 6. (a) Temperature field in deformation zone under the rolling velocity of 0.007, 0.05, 0.2, 0.5, 1; (b) Relationship between rolling velocity and the mean temperature of deformation zone.

Fig. 6(a) shows the thermal field of AZ31 alloy strips in the rolling deformation zone under a variety of rolling velocity, where the T_R = 250 °C, h_0 = 3 mm and ε = 20%. In the rolling deformation zone, the heated area increases as the rolling velocity decreases. Fig. 6(b) shows the relationship between T_D and v, it could be described by Eq. (3).

$$T_D = 113.018e^{-v/0.133} + 94.473\,. \tag{3}$$

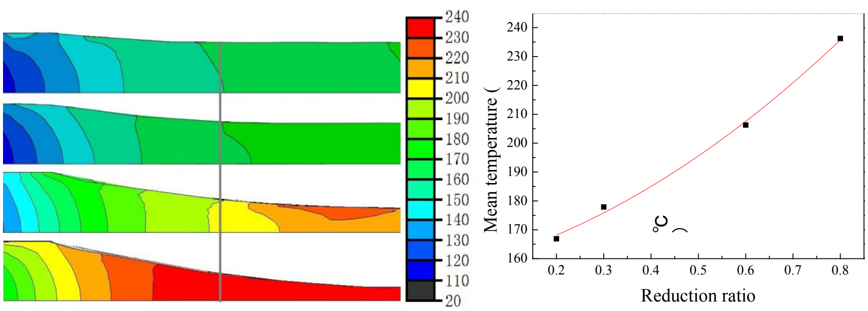

Fig. 7. (a) Temperature field in deformation zone under the reduction ratio of 20%, 30%, 50%, 80%; (b) Relationship between reduction ratio and the mean temperature of deformation zone.

Fig 7(a) shows the thermal field of AZ31 alloy strips in the rolling deformation zone under a variety of rolling reduction ratios, where the T_R is 250°C, h_0 is 3 mm, and v is 0.05 m/s. With increasing the rolling reduction ratio, the heated area in the strips increases. Fig 7(b) shows the relationship between T_D and ε, it could be described by Eq. (4).

$$T_D = 156.943 + 41.849\varepsilon + 70.788\varepsilon^2 . \tag{4}$$

Eqs. (1)-(4) show the relationship between the deformation temperature of strip and every factor separately. Here, we assumed that every factor above could affect the T_D with the same regularity when other factors are constant. Eqs. (1)-(4) should have the same value with the same parameters as h_0 = 3 mm, T_R = 250 °C, v = 0.05 m/s and ε = 20%. Finally, the deformation temperature in strips during the Hot-roller warm rolling process under the above factors could be obtained as Eq. (5).

$$T_D = 7.196(1 + 0.063T_R)(1 + 1.196e^{-v/0.133})(1 + 0.266\varepsilon + 0.451\varepsilon^2)(1 - 0.113h_0 + 0.0054h_0^2) . \tag{5}$$

Generally, AZ31 alloy of which plasticity is poor is especially in need of a prediction method to avoid cracking. By this equation, accurate operation parameters can be figured out to make AZ31 alloy strip reach a reasonable deformation temperature, so that the waste of materials could be reduced.

4. Conclusion

(1) The experiment result of AZ31 alloy strip forming by Hot-roller warm rolling was introduced. It is confirmed that this technique can improve plasticity of AZ31 alloy strip, and reduce its processing difficulty.

(2) A more accurate and useful prediction equation of AZ31 rolling temperature was proposed by using FEM method. The equation provides guidance for further research on AZ31 Hot-roller warm rolling process.

Acknowledgements

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